RESEARCH ARTICLE

Distribution and dynamics of particulate organic matter in Indian mangroves during dry period

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Abstract

The distribution and possible sources of particulate organic carbon (POC) and particulate nitrogen (PN) in seven mangroves ecosystems along the east and west coast of India were examined, to understand their contribution to coastal biogeochemistry. Suspended particulate matter (SPM) concentration in mangrove waters were about ~ 1.6-fold higher in west coast (Gulf of Kachchh (GOK), Mandovi-Zuari (MA-ZU) and Karwar-Kumta (KR-KU)], whereas the mean POC content in SPM along east coast [Sundarbans (SUN), Bhitarkanika (BHK), Coringa (COR) and Pichavaram-Muthupet (PI-MU)] was nearly two times higher than the west coast ($1.97 \pm 0.91\%$ and $1.06 \pm 0.29\%$), respectively. The results indicated that the influence of the land-based contaminants on the water quality parameters (dissolved oxygen, pH, salinity, nutrients and chlorophyll-a, etc.), which primarily regulated the distribution and transformation of organic carbon in these mangrove waters. Among the studied systems, an extremely high DOC/POC ratio (5.72 ± 1.64) with low pH and DO in COR waters clearly indicated the labile nature of the organic matter influenced by anthropogenic stress. Strong correlation between POC and PN indicated a similar origin in particulate organic matter. The ratios of POC/PN and POC/Chl-a showed significant spatial variation ranging from 5.5 to 18.7 and 126 to 1057, respectively. The results indicated that significant fraction of in-situ primary production contributed to particulate organic matter (POM) pool in all Indian mangrove waters except the GOK and the SUN waters, where sediment resuspension and mangrove derived organic matter were the dominant POM sources.

Keywords Suspended particulate matter · Particulate organic carbon · Dissolved organic carbon · Elemental stoichiometry · Mangrove waters · India

Introduction

Coastal vegetation including mangroves, marshes and seagrasses are well known for their concurrent contribution to the regional nutrient cycle, water column productivity and to the global carbon sink (Macreadie et al. 2019). Among these, mangroves are one of the most productive ecosystems in the world with a mean global primary production of 218 ± 72 Tg C year^{-1} (Bouillon et al. 2008). In tropical and sub-tropical conditions, mangroves are very important links between land and ocean and contribute to a large quantity of sediments and particulate organic matter (POM) to the ocean. For instance, the worldwide extent of total mangrove surface area is only 0.5%, yet they account for 10–15% to coastal sediment organic carbon and export to 10–11% of particulate carbon to the oceans (Alongi 2014). POM contributes to organic carbon burial in marine sediments (Duarte et al. 2005), and it can act as a significant source of nutrients for the primary producers in the coastal waters (Patra et al. 2016). Mangrove detritus are often correlated with total litter production (Mfilinge et al. 2005) which partially gets trapped within the shallow inter-tidal creeks. The other fraction of mangrove litters (~ 51%) is exported during ebb tide to the adjacent coastal waters and can significantly modify the carbon and nitrogen budgets and associated trophic status

of coastal ecosystems (Adame and Lovelock 2011; David et al. 2018). However, urbanization and excess import of anthropogenic pollutants with high lability could substantially increase the fraction of available food material to fuel microbial respiration (McCabe et al. 2021) and CO_2 fluxes from coastal waters (Abril et al. 2002). Earlier studies revealed that globally 28 ± 21 Tg of particulate organic carbon (POC) and 1.5 Tg of particulate nitrogen (PN), derived from dead mangrove biomass materials (mangrove detritus) are transported per annum to the adjacent coastal waters (Alongi 2013, 2014). Understanding the spatial variations in POC, PON and their ratios, and the in-situ processes, those regulate their distributions, could explain the regional biogeochemical cycles of carbon and nitrogen in the coastal environment. The molar ratio of particulate organic carbon and particulate organic nitrogen ratio (POC/PN) has been used for the discrimination of POM sources in coastal ocean waters (Balakrishna and Probst 2005). Particulate organic carbon to chlorophyll-a ratio (POC/Chl-a) revealed that water column chlorophyll-a is the dominant source of organic matter in coastal ocean waters (Cifuentes et al. 1988).

Indian mangroves with total cover of 5403 km^2 represent 3.3% of global mangroves and about 56% of global mangrove species (Ragavan et al. 2019). The east and west coast of India cover 56% and 32% of the total mangrove area of the country, whereas Island mangroves cover rest of the 12% (Purvaja et al. 2018). It is estimated that Indian mangroves transport about 0.58 Tg C as POC and 0.04 Tg N as PN per annum into the northern Indian Ocean (Ray et al. 2018).

A considerable number of studies on the carbon sequestration and storage by different mangrove ecosystems have been conducted along the Indian coast (Ray et al. 2018; Dutta et al. 2019). Higher seasonal fluxes of freshwater during the lean period from the submarine groundwater sources, causing relatively higher dissolved nutrient concentrations in the coastal waters, have already been reported (Rengarajan and Sarma 2015), from various mangrove ecosystems. However, no qualitative information on the elemental composition of SPM from Indian mangroves is available. Further, the number of studies on elemental stoichiometry in the suspended particles of inland waters including mangrove systems are scanty (Sterner 2011). Here, it is hypothesized that the changes in the C and N stoichiometry of suspended particles during the lean period are significantly influenced by the plant litter in Indian mangrove waters. This study aimed to characterize the SPM distributed along the salinity gradient of seven major Indian mangrove ecosystems, 4 along the east [Sundarbans (SUN) Bhitarkanika (BHK), Coringa (COR), Pichavaram-Muthupet (PI-MU)] and 3 along the west coast [Mandovi-Zuari (MA-ZU), Karwar-Kumta (KR-KU), Gulf of Kachchh (GOK)] of India during dry period. Further, the

possible interactions of SPM with primary production in these coastal waters were also determined.

Material and methods

Study area

The Indian peninsula intersects the north Indian Ocean into the Bay of Bengal (east coast) and the Arabian Sea (west coast). The west coast has a steep continental shelf and lacks major deltas and rivers and is dominated by sandy and rocky substratum (Purvaja et al. 2018), whereas the shallower east coast is characterised by major deltas and large estuarine systems. Major mangrove ecosystems from four coastal states along east coast and three coastal states along west coast were identified to understand the particulate organic matter dynamics (Fig. 1). Along the east coast SUN, BHK and COR witness meso-macro to meso tidal environment with moderate to high anthropogenic stresses linked to aquaculture and agricultural waste products (Reddy et al. 2021), whereas, PI-MU (Tamil Nadu) mangroves are microtidal (~ 1 m mean tidal range) in nature and mostly influenced by allochthonous materials generated from multiple land-based sources (Gupta et al. 2008). The mangroves situated in the west coast (MA-ZU, Goa and KA-KU, Karnataka) are mostly river dominated micro-tidal estuarine systems characterised with rapid deposition of terrigenous material (Hegde and Akshaya 2015) and activities such as illegal sand mining, unplanned tourism and other industrial accomplishments (Reddy et al. 2021). Whereas, peculiarly bedrock valley of GOK, Gujarat, characterised with pronounced tidal influence (macro-tidal regime), predominantly drains the black soil to the adjacent coastal waters. The important environmental features of the studied mangrove ecosystems are presented in Table 1.

Sampling

Surface water samples were collected from seven major mangrove ecosystems of India, during the dry period (from December 2016 to March 2017) (Fig. 1). Based on the areal extent and accessibility, duplicate water samples along the salinity gradient were collected from the mangrove waters along the east [SUN, West Bengal (21 locations); BHK, Odisha (17 locations); COR, Andhra Pradesh (11 locations); PI-MU, Tamil Nadu (11 locations)], and west [MA-ZU, Goa (17 locations), KR-KU, Karnataka (14 locations); and selected locations of GOK, Gujarat (7 locations)] coast of India. Samples for DOC were collected in amber coloured glass bottles, whereas POC samples were collected in tarson bottles and preserved in dark at 4 °C. In-situ measurements of water quality (temperature, salinity, pH and chlorophyll-a

Fig. 1 Map of the studied mangrove ecosystems along the east coast [(Sundarbans (SUN), Bhitarkanika (BHK), Coringa (COR) and Pichavaram and Muthupet (PI-MU)]. and west coast [(Gulf of Kachchh (GOK), Mandovi and Zuari (MA-ZU), and Karwar and Kumta (KR-KU)] of India. Blue circle indicates the studied ecosystems
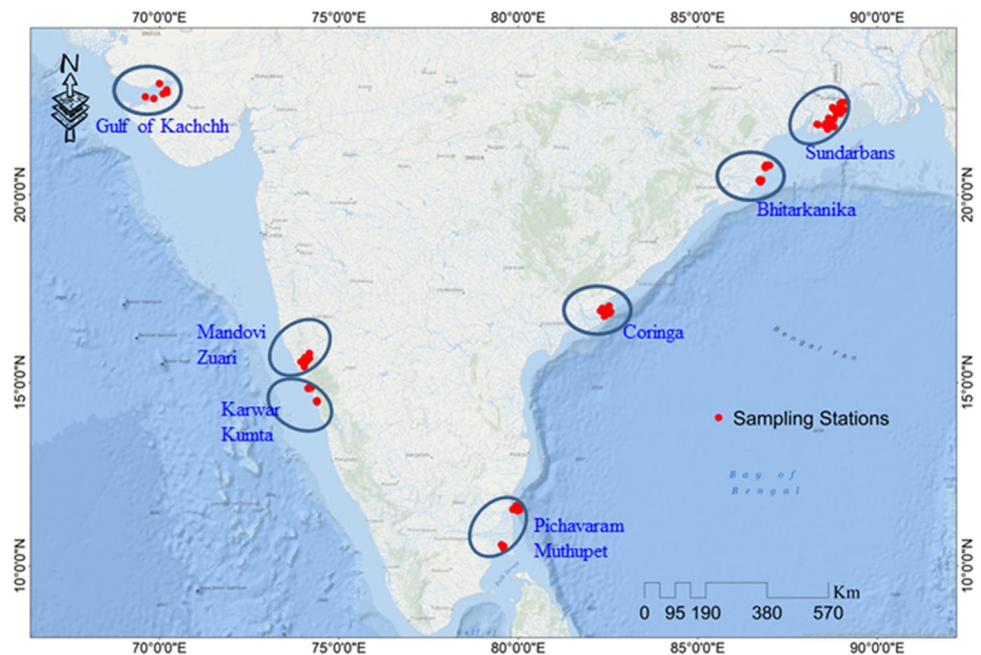
(Chl-*a*) were carried out using a pre-calibrated water quality probe (HYDROLAB sonde).

Laboratory analysis

Filtered water samples were analysed for nutrients following the standard spectrophotometric procedures (Grasshoff et al. 1999). The analytical precision of nitrate + nitrite ($NO_3 + NO_2$), ammonium and phosphate were ± 0.02, ± 0.02 and ± 0.01 μM, respectively. SPM was measured as the weight of material retained on 0.2 μm polycarbonate filter (Millipore) after passing 250 ml of water followed by washing with double-distilled and oven drying for 24 h (60 °C). Concentrations of DOC were measured after the water samples were filtered through pre-combusted (at 450 °C) 0.7 μm GF/F filters, using TOC analyser (Elementar Vario TOC Cube) following high temperature catalytic oxidation method. Potassium hydrogen phthalate solution (4 mM, KHP; EMSURE, Sigma-Aldrich, Germany, purity ≥ 99.95%) in carbon-free Milli-Q water was used to prepare the calibration standards for DOC analysis (Intergovernmental Oceanographic Commission 1994). Reference seawater and total blanks associated with DOC analysis were checked regularly. Total blanks associated with DOC analyses was about 10 μM and the analytical precision on triplicate injections was usually 3%. About 250 ml of water samples was filtered through a pre-combusted (4 h at 450 °C) GF/F filter (nominal pore size: 0.7 μm) at low vacuum and dried at 60 °C for at least 24 h. Filters were acid fumigated for 12 h in a desiccator to remove any trace of the inorganic carbon. Content of POC and PN on the filters were measured using an elemental analyser (Flash EA Thermo). The analytical precision for the

estimation of C and N content were $\pm 0.03\%$ and $\pm 0.02\%$ (relative standard deviation), respectively. Both POC and PON concentrations in suspended matter were expressed in mg L^{-1}.

Statistical analysis

ANOVA was performed separately for the samples collected along the east and west coast, to analyse the spatial variations in dissolved nutrients, SPM, POC, PON and POC/PON among the selected mangrove waters. Tukey post hoc multiple comparison test was performed to identify the difference among sample groups. Stepwise multiple regression analysis with the backward elimination technique was applied to explain the variability and to identify the major predictors of DOC/POC ratios for each of the studied mangrove ecosystems along the Indian coast. ANOVA and stepwise multiple regression analysis were performed using the MiniTab 16 software, and all plots were created using Grapher (version 5.0), and Microsoft excel.

Results and discussion

Hydrological characteristics of the Indian mangroves

Indian mangrove systems displayed a wide range of hydrological conditions during the non-monsoon season. During the study, surface water temperature varied between 25.52 and 33.76 °C (mean, 30.04 ± 2.31 °C) (Table 2). In the entire study, salinity in the mangrove waters ranged from 9

Table 1 Comparison between the studied mangrove ecosystems of their environmental features (The nomenclature for sediment texture was given following the classification of Flemming 2000)

	Mangrove	Latitude	Longitude	Area (km²)[**]	Sediment texture[#]	Sand (%)[#]	Silt (%)[#]	Clay (%)[#]	Elevation (m)	Tidal amplitude (m)[*]	Type of mangrove[**]	Rainfall (mm)[*]	Discharge (m³ s⁻¹)[*]	Dominant species[**]
East coast of India	Sundarbans (SUN)	21°32′–22°40′ N	88°05′–89° E	2207	Slightly sandy silt	9.23	79.6	11	3.3	7.01	Tide-dominated	1500–1800	–	A. alba, Ceriops E., agallacha, Ceriops decandra and Sonneratia apetala
	Bhitarkanika (BHK)	20°4′–20°8′N	86°45′–87° 50′ E	276	Sandy silt	27.5	69.2	2.9	1.66	2.82	Tide-dominated	1600	2121	A. marina, P. paludosa R. apiculata, A. officinalis and A. alba
	Coringa (COR)	16°44′–16° 53′N	82°14′–82°22′E	408	Sandy silt	39.8	55.5	4.6	0.87	2.1	River-dominated	1200–1300	3505	A. marina, E. agallocha, and A. officinalis
	Pichavaram and Muthupet (PI-MU)	10°25′–11°30′ N	79°39′–79°50′ E	119	Slightly sandy mud	15.0	60.0	25.0	0.34	0.64	River-dominated	1300	677	A. marina, Rhizophora, Excoecaria and Acanthus ilicifolius
West coast of India	Gulf of Kachchh (GOK)	21°30′–11.55′′N	72°43′53.68′′ E	1339	Sandy mud	27.6	38.8	34	2.04–4.15	10.9	Tide dominated	470	–	A. marina
	Mandovi and Zuari (MA-ZU)	15°21′–15° 31′ N	73° 45′–73° 59 E	33	Silty sand	70.4	29	0.6	1.5–2	2.7	River-dominated	3500	105	S. alba, R. mucronata and A. officinalis
	Karwar and Kumta(KR-KU)	14.391°–14.58° N	74.304–74.52° E	17	Silty sand	56.3	43.2	0.5		1.58[a]	River-dominated	3000	152	A. alba and A. marina

[#]Selvam 2003; [a]Kumar and Lal 2011; [*]Sarma et al. 2014; [**]Purvaja et al. 2018

Table 2 Mean water quality parameters recoded from the mangrove waters along the Indian coast

Mangrove	Water Temp. °C	Salinity (range)	DIN (μM)	Ammonium (μM)	DIP (μM)	DO saturation (%)	Chl-a (μg/l)	SPM (mg/l)	POC (mg/l)	PN (mg/l)	POC/PN	POC/Chl-a	POC/SPM	PN/SPM	pH
Sundarbans	27.1±0.74	6.27–17.1	39.2±25.6	18.3±18.8	1.92±0.89	81.4±5.9	1.86±0.41	99.8±52.5	1.89±0.48	0.11±0.07	18.6±4.8	1056±344	2.30±1.11	0.13±0.09	8.141±0.256
Bhitarkanika	30.6±0.93	12.1–23.7	72.4±11.3	64.8±10.5	0.05±0.01	95.8±12.1	6.48±4.73	103±25.2	1.79±0.76	0.19±0.04	11.8±2.83	489±413	1.81±0.76	0.20±0.07	7.401±0.344
Coringa	31.5±0.85	23.7–35.2	138±27.9	79.7±10.9	0.71±1.07	55.3±19.1	8.91±4.90	76.2±8.61	1.75±0.31	0.19±0.04	9.61±2.09	193±135	2.31±0.38	0.25±0.06	6.998±0.274
Pichavaram and Muthupet	27.3±0.81	27.1–42.0	20.7±14.5	9.66±6.09	2.86±2.65	74.5±23.3	9.87±7.81	109±19.9	1.27±0.42	0.23±0.08	5.52±0.99	194±138	1.16±0.29	0.21±0.06	7.715±0.286
Karwar and Kumta	32.2±1.08	4.02–37.1	20.4±2.53	19.8±2.35	0.42±0.02	114±9.61	4.3±1.37	227±42.9	1.71±0.6	0.17±0.06	9.50±2.41	425±72.6	0.82±0.22	0.08±0.03	7.68±0.149
Mandovi and Zuari	32.3±0.65	26.4–37.1	174±29.3	63.9±8.31	1.35±0.32	80.9±8.38	11.4±4.44	111±20.7	1.25±0.25	0.19±0.04	6.73±1.06	126±51.5	1.15±0.29	0.17±0.04	7.395±0.23
Gulf of Kachchh	29.5±1.51	40.1–41.5	251±73.9	152±76.7	32.7±5.61	96.0±6.49	5.07±2.01	162±24.2	1.97±0.27	0.33±0.06	6.06±0.89	404±120	1.19±0.09	0.19±0.04	7.526±0.11
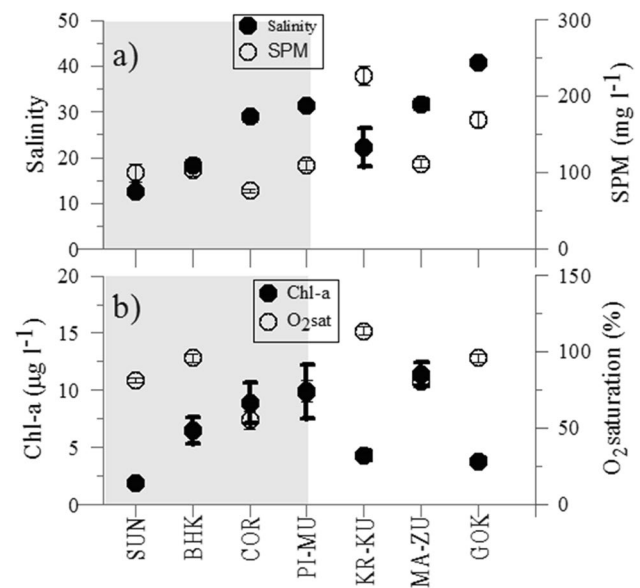
Fig. 2 Variations in **a** salinity and SPM (mg L^{-1}) and **b** Chl-a (μg/l) and O$_2$ saturation in the Indian mangroves. The light and dark shaded circles indicate east and west coast mangroves, respectively

to 41.0. The lowest mean salinity was recorded in Sundarban waters with a range of 10.78. The highest salinity range (33.07) from upstream to the downstream was recorded in the KR-KU waters. Consistently high salinity was recorded with very small spatial variation (range 1.43) in the GOK waters (Fig. 2a). The lower mean salinity in the mangrove waters of east coast could be attributed to the consistent lean discharge from the monsoonal rivers of east coast (including the eastern part of Indian Sundarbans), even in non-monsoonal periods (Rudra 2014).

The concentrations of the DIN ranged from 5.54 to 318 μM and the mean concentration (94.4 ± 82.5 μM) was higher than the concentrations reported earlier from the Indian mangroves (55.7 ± 107 μM; Rao et al. 2018). This concentration range of DIN was consistent with global range reported from mangrove waters (27.3–339.2 μM; Alongi 2013).

Significantly higher DIN concentrations from COR waters along the east coast and Mandovi-Zuari and GOK water along the west coast indicated a likely influence from various anthropogenic DIN sources to these mangrove waters. The range of DIP varied from 0.36 to 35.9 μM (3.4 ± 7.8) in Indian mangroves and was lower than previously reported values from Indian mangrove waters (8.57 ± 6.13 μM, Rao et al. 2018).

The mean N/P in these mangrove waters showed a very wide range from 7.2 (PI-MU) to 194.4 (COR). Similar to the earlier reports from Indian mangrove waters (Yuan et al. 2018; Maurya and Kumari 2021), limitation of bioavailable inorganic P (with respect to the Redfield ratio; N/P > 16) was

evident in SUN, BHK, COR, KR KU and MA ZU waters. Rapid removal of inorganic P from the mangrove water column could be attributed to the absorption by fine-grained particles and subsequent flocculation in the coastal environment (Singh et al. 2015). However, higher enrichment of bioavailable P in PI-MU and GOK waters resulted in limitation of dissolved N (Redfield ratio < 16). Compared to other Indian mangrove waters, exceptionally higher concentrations ($p < 0.001$) of dissolved ammonium (NH^{4+}) (203 ± 6.9 μM) and DIP (29.8 ± 5.5 μM) were recorded from GOK mangroves. In addition to the industrial influence and local characteristics of the parent rock, the higher concentrations of dissolved phosphates during non-monsoon season in GOK is largely attributed to transfer and diffusion of phosphorous from the sediment to surface water (Panseriyaa et al. 2021).

Suspended particulate matter (SPM) is a key component of coastal food web and a key variable of nutrient budgets (David et al. 2019). It varied from 44.4 to 290 mg L^{-1} (122 ± 55.5 mg L^{-1}) in the Indian mangrove waters during the study period (Fig. 2a). These values were higher than those reported earlier from Indian mangroves (88.6 ± 12.4 mg L^{-1}; Rao et al. 2018) and lower than Iranian mangroves (344 ± 180 mg L^{-1}; Ray and Shahraki 2016). Mean SPM concentrations were about ~ 1.6-fold higher in west coast than east coast of India. Further, the SPM concentrations of GOK (162 ± 24 mg/L) were highest compared to other mangrove systems and were attributed to sediment resuspension caused by high tidal amplitude at GOK region. The phytoplankton biomass, in terms of Chl-*a*, varied between 1.1 and 28.0 mg m^{-3} in Indian mangroves and it was consistent with earlier reports (Dutta et al. 2015). The mean of Chl-a concentration did not show any significant variation between west coast (6.5 ± 2.1 mg m^{-3}) and the east coast (6.1 ± 0.8 mg m^{-3}) during study period (Fig. 2b). Dissolved oxygen saturation, often regulated by in situ metabolic activities, varied between 61.9 and 131%, with the mean saturation of $85.1 \pm 12.5\%$ (east coast) and $94.2 \pm 16.7\%$ (west coast) in the mangrove waters (Fig. 2b). Chl-a showed significant positive correlation with dissolved oxygen saturation along the salinity gradients of BHK ($R^2 = 0.46$), KR-KU ($R^2 = 0.30$) and MA-ZU ($R^2 = 0.39$). However, in the rest of the systems, no clear relationship between Chl-a and DO saturation was recorded.

Coastal acidification and deoxygenation, inextricably associated through the process of heterotrophic respiration, could occur at extreme levels when the coastal zone receives a large quantity of natural/anthropogenic nutrient and organic matters (Gobler and Baumann 2016). Dissolved nutrients (dissolved inorganic nitrogen in particular) were reported considerably high in the COR waters in east coast of India and in mangrove waters of MA–ZU and GOK of west coast of India (Maurya and Kumari 2021). These results clearly indicated the influence of intense anthropogenic

activities in these mangrove waters compared to the other mangroves. Low mean pH (pH < 7.7; except SUN waters) and persistence of DO under-saturation (except KA-KU waters) in most of these mangroves revealed the dominance of heterotrophic respiration and depletion of dissolved O_2 in the water column. Among all the studied systems, moderate to strong negative correlations between DOC and DO saturation were recorded for COR ($r^2 = 0.33$, $p < 0.001$) (Fig. 3a) and GOK ($r^2 = 0.61$, $p < 0.001$) (Fig. 3b). These results further indicated the likely influence of labile contaminants in reducing DO saturation of mangrove waters. Intensification of land-based sources of contaminants and organic matter could further deteriorate the mangrove water quality and reduce the growth and survival of early-life stage aquatic organisms (Baumann et al. 2012) in this unique intertidal environment.

Variations in particulate organic carbon and nitrogen during dry period

The dynamics of POM are likely to influence the whole food web in the mangrove ecosystem (Bouillon et al. 2002). Concentrations of particulate organic carbon and nitrogen (POC, PN), suspended in the surface waters of the mangrove ecosystems along the Indian coast ranged from 0.74
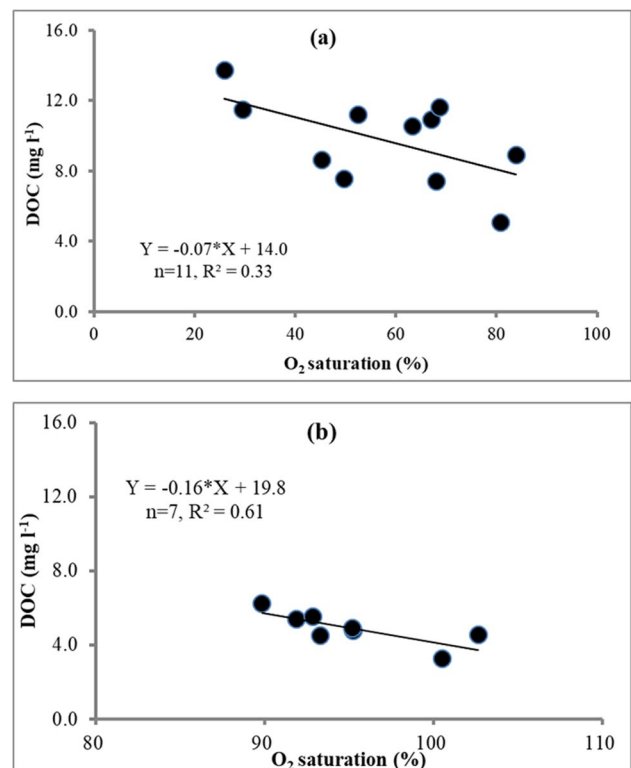

Fig. 3 Correlations between DOC and O_2 saturation for **a** Coringa, **b** Gulf of Kachchh mangroves waters along the Indian coast

to 3.55 mg L^{-1} (1.67 ± 0.55 mg L^{-1}; Fig. 4a) and 0.04 to 0.42 mg L^{-1} (0.18 ± 0.08 mg L^{-1}; Fig. 4b), respectively. These POC and PN concentrations were higher than the earlier reports from Indian mangrove waters (0.2 to 1.21 mg L^{-1}, 0.02 to 0.21 mg L^{-1}, respectively, Ray and Shahraki 2016; Ray et al. 2018) and Iriomote Island mangrove, Japan (0.76 ± 1.32 mg L^{-1} and 0.08 ± 0.12 mg L^{-1}; Akhand et al. 2021). Relatively higher concentrations of mean POC were recorded in the east coast (1.74 ± 0.57 mg L^{-1}) than the west coast (1.55 ± 0.49 mg L^{-1}) mangroves (Table 2, Fig. 4a). The mean concentration of PN in the west coast mangrove waters (0.21 ± 0.08 mg L^{-1}) was relatively higher than the east coast (0.17 ± 0.08 mg L^{-1}). However, the spatial variations of both in POC and PN concentrations between the east and west coast mangrove waters were statistically insignificant ($p > 0.05$). The %OC and %ON [measured as % OC = (POC/SPM)*100 and % ON = (PN/SPM)*100] indicated the percentage of organic carbon and organic nitrogen present in suspended particulate matter (Sarma et al. 2014). %OC and %ON of the Indian mangrove waters varied from 0.57 to 5.26% (1.61 ± 0.86%; Fig. 4a) and 0.02 to 0.44% (0.17 ± 0.08%; Fig. 4b), respectively during the study period. The percent of POC in SPM of east coast (1.97 ± 0.91%) was almost twice the value of west coast (1.06 ± 0.29%) ($p < 0.001$). Among the studied mangrove ecosystems, the lowest POC content (1.25 ± 0.25%) in SPM was found in the MA-ZU mangrove waters along the west coast of India. This could be attributed to limited fresh water flow from the upstream and occurrence of lower amount of finer particles (clay and silt) in the mangrove sediments along this coast

Fig. 4 Variations in **a** POC (mg L^{-1}) and %OC **b** PN (mg L^{-1}) and %ON in the Indian mangroves. The light and dark shaded circles indicate east and west coast mangroves, respectively

(Reddy et al. 2021). Further large variability of land use in the catchment areas (17 to 2207 km^2, Table 1) and relatively limited cover of mangrove vegetation along SW coast could explain the low POC and PN content in SPM. Predicted intensification of precipitation, one of the major regulating factor of mangrove POC export (Adame and Lovelock 2011), of about 7% per 1 °C of warming from sub-daily up to seasonal time scales, could significantly (Arias et al. 2021) modify the existing carbon export and the net budget from these mangrove systems along the Indian coast.

Ratios of particulate and dissolved matter

Concentrations of dissolved organic carbon (DOC) in the studied mangrove waters ranged between 1.9 and 13.7 (4.59 ± 2.28) mg L^{-1} with the highest mean DOC concentrations observed in COR (9.75 ± 2.46 mg L^{-1}, $p < 0.001$) waters, followed by GOK (4.80 ± 1.0 mg L^{-1}). The mean DOC concentrations recorded from different systems in the present study were relatively higher than those reported from Indian Sundarbans (2.57–3.94 mg L^{-1}; Ray et al. 2015) and were comparable with those reported from Sinnamary estuarine mangrove of French Guiana, South America (8.50 ± 1.01 mg L^{-1}; Ray et al. 2020).

Organic carbon (OC) produced within mangrove ecosystems are subjected to seaward export during the ebb tide either in the form of dissolved organic carbon (DOC) or as particulate organic carbon (POC). The DOC/POC ratio in coastal waters often indicates the degree of partitioning of organic carbon between the dissolved and particulate fractions. The DOC/POC ratios for Indian mangrove waters ranged between 0.83 and 8.20 (3.05 ± 1.56) (Fig. 5a) and was higher than those values reported earlier from Sundarban mangrove waters (0.50 to 3.39; Dutta et al. 2019) during the non-monsoon season. Between DOC and POC, the later plays a bigger role in the export and gravitational settling of phytoplankton derived OC into deep sea and associated carbon cycle (Kharbush et al. 2020). A higher DOC/POC ratio in the coastal waters indicates the higher availability of labile organic carbon. Even though the DOC/POC ratios of most of the studies systems were found similar, exceptionally higher DOC in COR waters resulted five folds higher DOC/POC (5.72 ± 1.64) ratio than the mean ratio of 0.9 for the Asian rivers (Ludwig et al. 1996). These results suggested that a significant fraction of the POC gets modified through microbial activities to DOC (9.75 ± 2.46 mg L^{-1}) (Table 2, Fig. 5a) in COR (Robin et al. 2016; Krishna et al. 2018). Additionally, the mangrove waters of COR showed low mean pH (6.998 ± 0.274) and DO saturation (55.3 ± 19.2%) (Table 2) and the suspended matter was characterised with the highest mean OC content (2.31 ± 0.38%). Enhanced transport of terrestrial inputs from agriculture and aquaculture sectors to the COR mangrove ecosystem (Reddy et al. 2021) has the
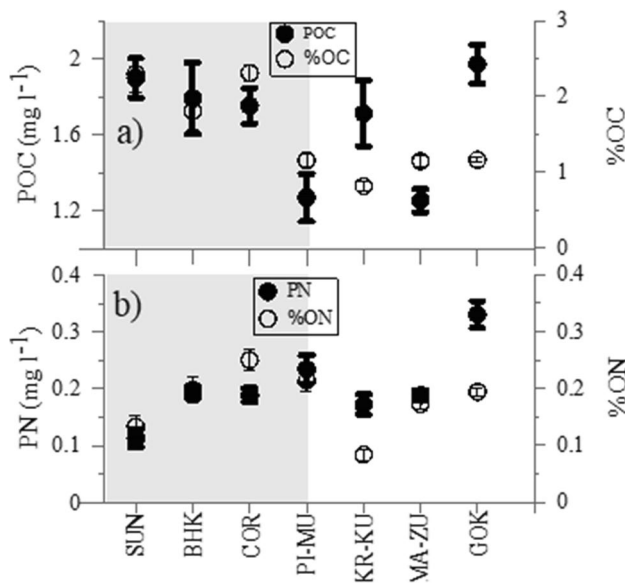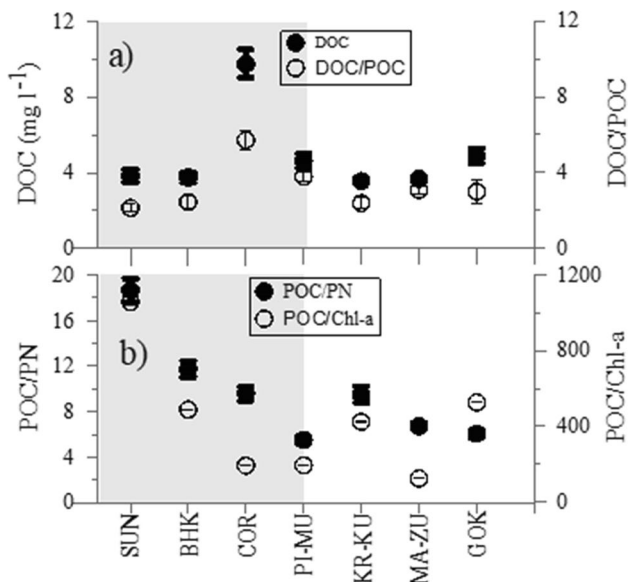
Fig. 5 Variations of mean **a** DOC (mg L^{-1}) and DOC/POC, **b** POC/PN and POC/Chl-a in the Indian mangrove waters. The light and dark shaded circles represents the mangroves of east and west coasts of India, respectively

potentials to stimulate the microbial degradation of DOC within the estuarine zone and decrease regional export of DOC to the ocean (Lønborg et al. 2020). Terrestrial DOC could also substantially dampen the primary production and result in high CO_2 supersaturated waters in the nearshore areas by inducing rapid remineralization and strong light attenuation (Fransner et al. 2019). With the increase in basin population and alteration in reservoir water capacity, an exponential increase in total DOC fluxes and decreasing total POC fluxes to the marginal seas have been reported in the last few decades from the Chinese rivers (Liu et al. 2020). However, no such information on the temporal variability in DOC and POC transport to coastal waters has been reported from Indian water.

Sources of POC and PN along the Indian coast using POC/PN and POC/Chl-a ratios

Elemental ratios of C and N (or POC/PN) in suspended matter *has* been widely used in conjugation with other environmental proxies to trace the predominant source of organic matter in aquatic system (Tamooh et al. 2020). POC and PN were strongly correlated in all mangrove waters along the salinity gradient, indicating their identical origin (Supplementary Information; Fig S1) within the individual ecosystems, during non-monsoon period. The elemental POC/PN molar ratios in the SPM of the studied mangrove waters ranged between 4.6 and 28.2 (10.7 ± 5.5), which was similar to those reported from Sinnamary mangroves (2.8 to 28.5; Ray et al. 2018). The POC/PN ratio was highest at SUN

(14.3 ± 5.4) followed by BHK (11.8 ± 2.83). The POC/PN ratios in the suspended particles of PI-MU, MA-ZU and GOK mangrove waters were close to the marine phytoplankton (6–9.; Redfield 1958), whereas higher values in the other studied systems indicated likely influences of mangrove litters. Further, the relationship between POC and Chl-a has been used to understand the role of phytoplankton in POM production (Hung et al. 2013; Liu et al. 2019) in these mangrove waters. The contribution of live biomass to the POC pool (represented as POC/Chl-a) varied between 42 and 1554 (mean 446 ± 42.5) in Indian mangrove waters. Among all the systems, an exceptionally higher mean POC/Chl-a ratio was recorded at SUN waters (1056 ± 344). On the contrary, lower mean POC/Chl-a values (< 200; Cifuentes et al. 1988) along the PI-MU mangroves could be attributed to moderately high contribution of Chl-a (9.87 ± 7.81 and 8.46 ± 4.95 mg m^{-3}, respectively) in POC pool indicating the significance of live phytoplankton biomass in these regions. Significantly higher mean elemental POC/PN ratios in the suspended particles, recorded during the non-monsoon season, from SUN and BHK mangrove waters were consistent with those of the mangrove plant derived materials (POC/PN = 27.1 ± 10.4; Tue et al. 2012). These values were further supported by the high POC/Chl-a ratios. This study revealed the high potentials of suspended particles of these two mangrove systems, in coastal carbon burial and restricting mangrove derived refractory POC within a few kilometres offshore owing to local geomorphology (Alongi 2014). The POC/PN and POC/Chl-a ratios, particularly from PI-MU (5.52 ± 0.3 and 195 ± 41, respectively) and MA-ZU (6.73 ± 0.26 and 126 ± 12, respectively), indicate that marine plankton predominantly contributed to the POC pool of mangrove ecosystems (Savoye et al. 2003). On the contrary, the ratios of POC/Chl-a observed from GOK (308 ± 72) and KA-KU (454 ± 36) was significantly higher (Fig. 5b). High POC/Chl-a ratios indicated faster degradation of Chl-a than the whole POC pool by the heterotrophic bacteria (Cifuentes et al. 1988; Bueno et al. 2020). In addition to that, Fig. 6a, b, c indicate likely contribution from both phyto-detritus and sediment resuspension to the POM pool in macro-tidal GOK mangrove ecosystem. Overall, the relationship between POC/PN and POC/Chl-a ratios indicates that POM concentrations in SUN, BHK and KR-KU waters are strongly influenced by terrestrial inputs and mangrove litter (Fig. 7). Whereas, in COR waters, contributions from mixed sources (mangrove litter and other degraded aquatic particles) were dominant in the available POM. Along the west coast, the POM in the MA-ZU waters are characterised by phytoplankton, present in the water column.

Particularly, in GOK region, relatively higher SPM (162 ± 24 mg/L) and POC/Chl-a ratios were associated with low Chl-a (3.8 ± 0.6) compared to other mangrove waters. The positive relationship between POC and SPM
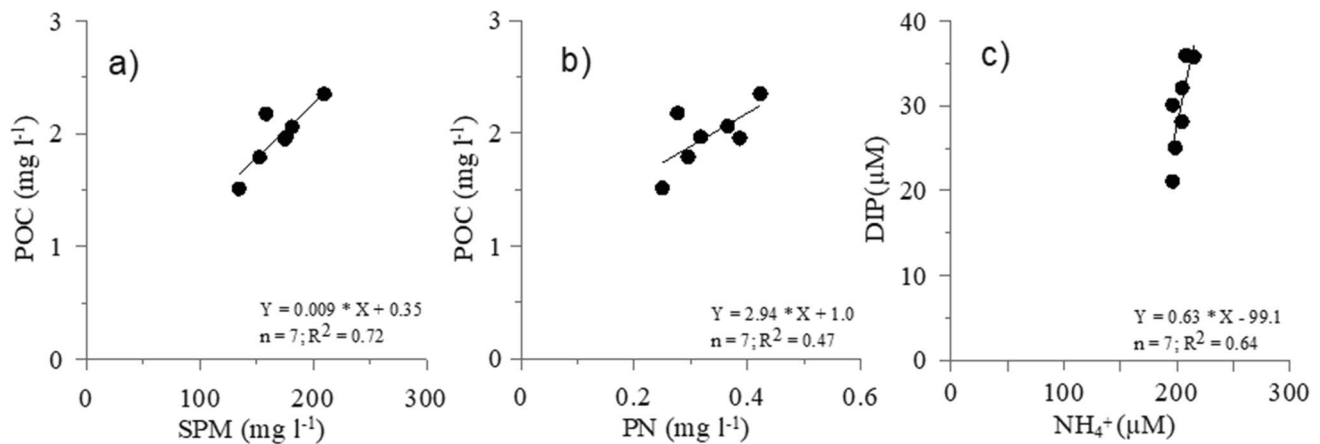
Fig. 6 Correlations between **a** SPM and POC; **b** POC and PN; **c** DIP and NH_4^+; **d** Chl-a and SPM for GOK, mangroves
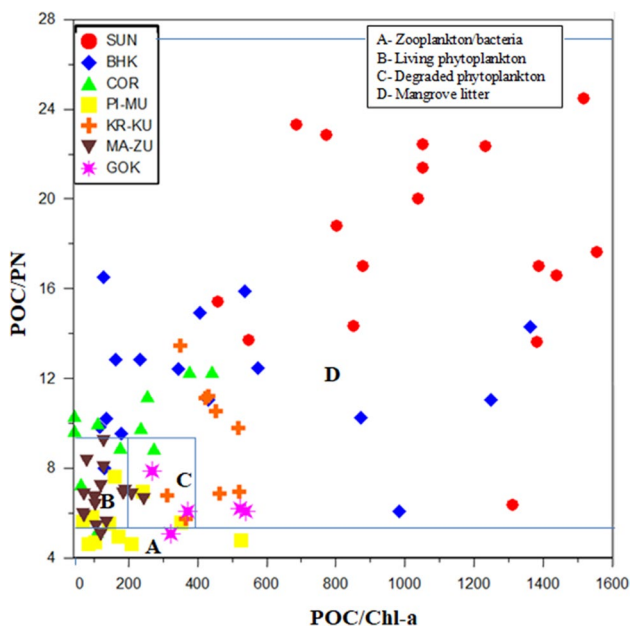

Fig. 7 Relationship between POC/PN ratios and POC/Chl-a ratios for **a** Sundarbans (SUN), **b** Bhitarkanika (BHK), **c** Coringa (COR), **d** Pichavaram and Muthupeet (PI-MU), **e** Gulf of Kachchh (GOK), **f** Mandovi and Zuari (MA-ZU), and **g** Karwar and Kumta (KR-KU) along the estuarine gradient of the Indian mangrove waters

concentrations ($r^2 = 0.72$, $p < 0.001$, Fig. 6a) and POC and PN ($r^2 = 0.47$, $p < 0.001$, Fig. 6b) indicating particulate pool of organic C and N are coupled by identical biogeochemical mechanism (Kaiser et al. 2014) in these mangrove waters. Further, high concentrations of dissolved NH_4^+ and DIP and the positive relationship between them ($r^2 = 0.64$, $p < 0.001$, Fig. 6c) in these waters suggested that these nutrients may be originated from common sources and possibly influenced by nutrient adsorption–desorption by suspended particulate under high tidal influence (Clavero et al. 2000). Macro-tidal

mangrove waters of this region (GOK) experiences periodic re-suspension of surface sediments (Table 1). Strong tidal circulation, shallow bathymetry and presence of fine-grained sediments control the extent of resuspension (Ramaswamy et al. 2007) and trapping of suspended matter and POC (both passive and active accumulation) within these mangrove forest and adjacent waterways (Alongi 2014).

Factors influencing transformation of POC

Between DOC and POC, the latter is considered as a key component of the biological pump and associated C cycle, due to its major transformation pathway by which OC produced from various autochthonous origins is exported from the surface waters to the marine sediments (primarily by gravitational settling) (Cavan et al. 2015). The relationship between DOC and POC is often being used as a potential indicator for the in-situ transformation of POM (Alvarez-Cobelas et al. 2012) along the salinity gradient of coastal waters. In mangrove waters, where POC can be generated from multiple origins including mangrove litter, activity of plankton, sediment resuspension and other allochthonous sources, the biogeochemical transformation pathway could be depended on the in-situ environmental factors. In the stepwise multiple regression analysis with backward elimination technique, the predictor variables used were temperature, salinity, pH, Chl-a, SPM, DO saturation and the results are given in Table 3.

The variability of DOC/POC ratio for Sundarban waters was explained (43.8%) by water temperature, salinity and SPM concentration. This result indicated the significance of mangrove litter contributing to the SPM, and its resistance to transformation into the more labile form. A total of 48.2% variability of the DOC/POC ratio in Bhitarkanika waters was explained by salinity and pH, which often determine the distribution of phytoplankton in the water column. In

Table 3 The results of the stepwise multiple regression model for different mangrove ecosystems of India

System	r^2	p	F	N	Regression equation
Sundarban	43.8	0.019	4.38	20	DOC/POC =—11.7 + 0.524 T—0.0034 S—0.00483 SPM
Bhitarkanika	48.2	0.007	6.97	18	DOC/POC = 14.1—0.0934 S—1.35 pH
Coringa	69.6	0.027	5.58	12	DOC/POC = 17.4—1.27 pH—0.0490 DO Sat
Pichavaram-Muthupet	63.9	0.01	7.97	12	DOC/POC =—17.8 + 3.48 pH—0.0716 DO Sat
Karwar and Kumta	64.3	0.008	6.6	15	DOC/POC = -6.23—0.422 Chl a + 0.904 pH + 0.0300 DO Sat
Mandovi and Zuari	43.4	0.014	5.73	18	DOC/POC = 7.33—0.0179 SPM—0.0276 DO Sat
Gulf of Kachchh	78.4	0.022	9.08	8	DOC/POC =—64.5 + 1.72 Salinity—0.0320 DO Sat

COR and PI-MU mangrove waters, variability of the DOC/POC ratio was primarily determined (69.6%) by water pH and dissolved oxygen in the water column. Along the West coast, the DOC/POC ratio showed a strong dependence on dissolved oxygen saturation, which was closely connected with anthropogenic stresses in the mangrove waters. Overall, the result indicated that higher production/lower consumption of DOC (Calleja et al. 2019) relative to available POC is favoured under the oxygen depleted conditions in these mangrove water columns. These results further support the earlier observations linked to the increase in POC lability and intensity of mineralization with pollution from nine contrasting European estuaries (Abril et al. 2002). Deoxygenation of mangrove waters by increase either in surface temperature or in land-based pollutants could therefore increase the DOC flux or decrease the POC fluxes to the coastal waters. These alterations in the carbon fluxes to the marginal seas can have substantial impacts (Liu et al. 2020) on the aquatic environment and ecology and regional climate.

Conclusions

Mangrove ecosystems along the Indian coast substantially contribute to the organic carbon pool across the intertidal landscape, and are regularly influenced by various anthropogenic activities. The present study on the distribution of particulate organic matter in the mangrove waters of India revealed that the relative concentrations of %OC and %ON present in SPM along the east coast were higher than those on the west coast of India. POC and PN were strongly correlated in all mangrove waters along the salinity gradient, indicating their identical origin (i.e., particulate organic matter) in the individual ecosystems, during the non-monsoon period. Preliminary results from the major mangrove ecosystems of India indicated that mangrove litter, marine phytoplankton and marine sediment likely form the dominant POC pool for these unique ecosystems. Isotopic signatures of carbon (δ13C) and nitrogen (δ15N) in mangrove POM are necessary to confirm their origins and transformation through biogeochemical processes.

Slow bacterial hydrolysis of structurally complex organic matter and prevailing reducing conditions influences the anaerobic decomposition rates and primarily determines the stability of particulate organic matter in the mangrove water columns (Kristensen et al. 1995). In particular, high DOC concentrations and DOC/POC ratios in the mangrove waters of COR indicated rapid transformation of organic carbon from particulate to more labile dissolved forms. Any alteration in local geomorphic settings in the coastal areas or changes in particle transport from the upstream areas may affect the production, storage and fluxes of carbon within the mangrove ecosystems and the subsequent export to the adjacent coastal waters. Further, ecological changes (crab burrowing activity, primary production litter fall etc.) caused by various environmental factors (temperature, rainfall, detrital outwelling, coastal currents etc.) are likely to have significant impacts on the transformation and export of to the adjacent coastal waters. Conservation and restoration of intertidal landscape, characterised by healthy mangrove vegetation, are therefore critical to sustain ecological balance in coastal environments. Detailed studies on the origin and fate of different forms of carbon together with quantification of anthropogenic inputs and tidal fluxes will help to elucidate their functional role in mangrove carbon cycle along the Indian coast.

Author contribution MHK Prasad executed the study and prepared the first draft of the manuscript. DG, PR, YR, PSA, GS, KB and RR led the sampling design. All authors contributed with data collection. MHK Prasad analysed the sediment samples, and YR, PSA, GS, KB, RRS analysed the water samples and interpreted the datasets. MHK Prasad, DG, GS and PSA contributed in the statistical analysis and reviewing the manuscript. PR and RR contributed with overall guidance and project administration. All authors read and approved the final manuscript.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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